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Biomass to liquid: A prospective challenge to research and development in 21st century

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ABSTRACT

The biomass to liquid refineries need to build on the need for sustainable chemical products through modern and proven green chemical technologies such as bioprocessing including pyrolysis, Fisher Tropsch, and other catalytic processes. This review focuses on cost effective technologies and the processes to convert biomass into useful liquid biofuels and bioproducts. One of the most promising options to produce transportation fuels from biomass is the so-called biomass to-liquid (BTL) route, in which biomass is converted to syngas from which high-quality Fischer–Tropsch (FT) fuels are synthesized. Pretreatment of biomass is an important part of the BTL route, both to allow feeding of the biomass into the selected entrained-flow gasifier and to reduce transport costs by densification. A large-scale, central, overseas BTL synthesis plant would be the most attractive route for BTL production and it identifies biomass-to-liquid (BTL) fuels as the most promising way to accomplish the target. The evaluation of the future role of BTL is difficult due to complex and uncertain interdependencies between factors of influence. This study elaborates a life cycle assessment of using of BTL-fuels and the possible implementation of BTL-fuel production processes would potentially help to achieve this goal. The emissions of greenhouse gases due to transport services could be reduced by 28–69% with the BTL-processes using straw, forest wood or short-rotation wood as a biomass input. The reduction potential concerning non-renewable energy resources varies between 37% and 61%. BTL-fuel from forest wood is an interesting option to reduce the greenhouse gas emissions and environmental impacts. The LCA study shows that it is possible to produce BTL-fuels, which are competitive to fossil fuels from an environmental point of view. But, it also shows that for the use of agricultural biomass further improvements in the life cycle would be necessary in order to avoid higher environmental impacts than for fossil fuels. There is no general conclusion concerning the comparison of BTL-fuels with other renewable or fossil fuels due to the variety of different conversion concepts and possible biomass resources.

Contents

Abbreviations: BTL, biomass-to-liquid fuel including FT-fuel, methanol and DME produced from synthesis gas; BMTL, BTL (multi step) process; SNG, synthetic natural gas; CEF-D, centralized entrained flow gasification; CFB, circulating fluidized bed; CFB-D, centralized autothermal circulating fluidized bed gasification; MTS, methanol-to-synfuel; EUCAR, European Commission with the European Council for Automotive R&D; O&M, operation and maintenance; SD, sun diesel; FC, fuel cell; SI ICE, petrol engine; CI ICE, diesel engine; PEM, proton exchange membrane; H_2CO, formaldehyde; CH_3OH, methanol; MTBE, methyl-tertiary-butyl-ether; DMFC, direct methanol fuel cells; CH_3OCH_3, DME; H_2, hydrogen; CNG, compressed natural gas; CH, Switzerland; CTL, coal to liquid; DME, dimethylether; EI'99, Eco-indicator 99 (H, A); FT, Fischer–Tropsch (synthesis); GWP, global warming potential; GHG, greenhouse gases; GTL, gas-to-liquid; HHV, higher (upper) heating value; ISO, International Organization for Standardization; LCA, life cycle assessment; LCI, life cycle inventory analysis; LCIA, life cycle impact assessment; LHV, lower heating value; LPG, liquid petroleum gas; PM, particulate matter; Pt points, Eco-indicator 99 (H, A) or ecological scarcity 2006; RENEW, renewable fuels for advanced power trains; SNG, synthetic natural gas.

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1. Introduction

Biomass to liquid is a process by which, liquid biofuels produced from biomass. A generation with potential for the future: biomass-to-liquid fuels promise high returns and CO_2 neutrality as well as ideal prospects for large-scale production. Lignocellulose provides the basis for this fuel such as straw, wood, energy crops, agricultural waste – nearly all sorts of solid biomass in the world can be considered for the production of BTL biofuel. To produce BTL biofuel, biomass is converted into synthesis gas, which is subsequently processed into synthetic biofuels. Just as in the production of bioethanol from lignocellulose, the entire plant is used for BTL biofuels. This increases yields, while at the same time reducing the land that needs to be cultivated [1,2]. BTL fuels also have a very special property: their quality is even better than that of fossil fuels. They excel through significantly lower CO_2 emissions, zero emission of particulate matter, low NO_x emissions and an adjustable product quality (octane and cetane number). As a result they can be used pure or as a blend in vehicles without the engine having to be modified. Biomass to liquid (BTL) is one of the most promising processes available in the fuel sector. The greatest advantages of the resulting synthetic biofuel lie in the high biomass yield (up to 4000 l/ha), its high potential to reduce CO_2 emissions by over 90% and its high quality, which is not subject to any limitations of use in either today's engine or foreseeable next-generation engines. In its fuel strategy, the German government has therefore stated that BTL fuels have great potential for securing supply, mitigating climate change and providing added value in rural areas, and has decided to promote the development of this innovative fuel in a number of ways. German industry has earned itself a leading position in the global development of this technology. Biomass to liquid (BTL) or BMTL is a (multi step) process to produce liquid biofuels from biomass: the process uses the whole plant to improve the carbon dioxide balance and increase yield [3].

- The Fischer–Tropsch process is used to produce synfuels from gasified biomass. While biodiesel and bio-ethanol production so far only use parts of a plant i.e. oil, sugar, starch or cellulose, BTL production uses the whole plant which is gasified by gasification. The result is that for BTL, less land area is required per unit of energy produced compared with biodiesel or bioethanol.
- Flash pyrolysis – producing bio-oil, char and gas at temperatures between 350 and 550 °C and residence times <1 s (also called anhydrous pyrolysis).
- Catalytic depolymerization – using heat and catalysts to separate usable diesel fuel from hydrocarbon wastes.

The term BTL is applied to synthetic fuels made from biomass through a thermo chemical route. The objective is to produce fuel components that are similar to those of current fossil-derived petrol (gasoline) and diesel fuels and hence can be used in existing fuel distribution systems and with standard engines. They are also known as synfuels. Although the processes for production of BTL are well known and have been applied using fossil-feedstocks such as methane (GTL) or coal, commercial biofuels based on these technologies are not currently available in the market place [4]. However, BTL research & development in Europe is gathering momentum and the world's first commercial BTL plant is under construction in Frieberg Saxony, utilizing the Choren Carbo-V® Process.

2. Biomass-to-liquid (current process)

Currently, the major biomass-to-liquid production processes are gas-to-liquid conversion and pyrolysis. Both processes employ heat and chemical reactions to convert biomass into fuels, chemicals and power. The products of both processes are cleaner and more efficient than the solid biomass from which they were derived. Another benefit is that biomass-to-liquid processes can convert types of biomass such as wood and agricultural residues that are difficult to handle using other biofuel production processes.

2.1. Pyrolysis

In this process, biomass is heated in the absence of oxygen to produce liquid pyrolysis oil sometimes called bio-oil, which can be burned like fuel oil or refined into chemicals and fuels. Several commercial facilities produce energy and chemicals from pyrolysis oil. Upgrading pyrolysis oil to high-quality hydrocarbon fuels has been demonstrated at a non-commercial scale.

2.2. Gasification

Gasification is not a new technology however its use for the conversion of biomass into a viable fuel has only been investigated for past thirty years. Syngas can be produced from biomass by two routes namely catalytic and noncatalytic. Noncatalytic process requires a very high temperature of operation, as high as 1300 °C, whereas catalytic process can be operated at substantially lower temperature. With more advances in the catalysis, the temperature requirement is expected to go downward further from the current value of about 900 °C [5]. The gasification step involves reacting biomass with air, oxygen, or steam to produce a gaseous mixture of CO, CO_2, H_2, CH_4, and N_2 either known as producer gas or synthesis or syngas, depending on the relative proportions of the component gases. In terms of producing synthetic fuels from biomass, the Choren process is the most advanced. In the process developed by the company of the same name, the gasification of the biomass is followed by Fischer–Tropsch synthesis. The final product is a highly pure fuel – depending on the type of synthesis, more diesel, more petrol or more kerosene is produced. The company from Freiberg in Saxony currently owns the world's only facility that can produce a biomass-to-liquid fuel (BTL). The mineral oil company Shell is now collaborating with Choren to further develop and expand this facility.

2.3. Liquefaction

In the direct liquefaction, the biomass is converted into a liquid fuel without a synthetic gas being produced in-between. This promises a considerable improvement in thermal efficiency compared with the synthesis gas process. In this process, liquid is obtained by thermo-chemical conversion at low temperature and high pressure using a catalyst in the presence of hydrogen.

2.4. The Fischer–Tropsch process

Fischer–Tropsch (F–T) diesel is produced by converting synthesis gas (syngas) a mixture of carbon monoxide and hydrogen produced from fossil fuels such as natural gas and coal or biomass into liquid diesel. In 1923, Franz Fischer and Hans Tropsch first studied conversion of coal-derived syngas into useful compounds (diesel is one of many chemicals and fuels that can be derived from syngas), using what was to become known as Fischer–Tropsch synthesis. Key to the process is catalysts: substances that facilitate a chemical reaction but are not consumed by the reaction. A schematic of the overall process can be shown in three steps with each step taking place in the presence of a specific catalyst:

1. Syngas formation: Old hydrocarbon + Oxygen → Syngas
2. Fischer–Tropsch reaction: Syngas → New Hydrocarbon + Water
3. Refining: New hydrocarbon → Fuels, Chemicals, etc.

The benefit of the process lies in converting a relatively inflexible energy source into a variety of products that meet specific needs.

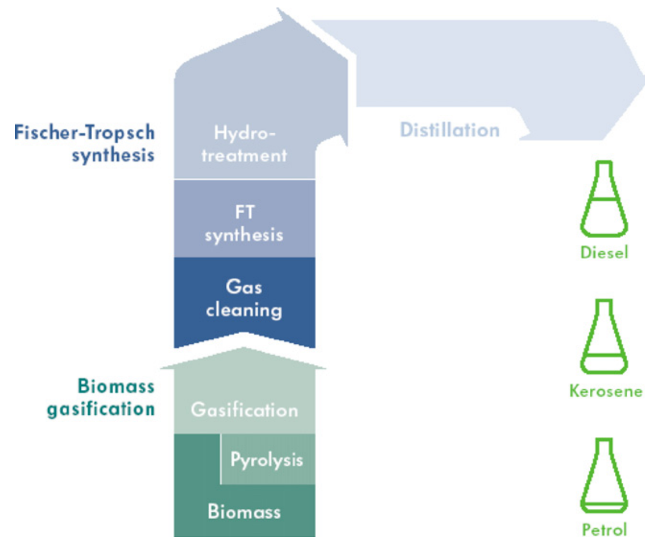


Fig. 1. Main steps of BTL production of fuels.

Because petroleum-based transportation fuels are in high demand worldwide.

The production process for BTL starts with grinding and drying of biomass which is then formed into pellets. Feedstock biomasses that may be used in this process include wood, straw, corn, garbage, and sewage-sludge. The biomass-pellets are diverted into a gas (smouldering gas) and solid fraction (charcoal) in a low temperature gasification process and transformed into a synthetic gas in a second step. After purification the gas is liquefied in a so called "Fischer–Tropsch" reaction, in which carbon monoxide (CO) and hydrogen (H) react and form carbo-hydrogen chains. The resulting paraffin-like liquid isomerizes to increase stability and then distilled or "hydro-treated". In this step, the specifications of the fuel can be fine-tuned to match the requirements of the engines by altering the form or length of the fuel molecules [5]. This fine-tuning is not possible in the currently used standards refining process for diesel or gasoline, hence BTL is also nicknamed "designer fuel". Sixty percent of the distillate can be used directly as a diesel fuel, while the other fractions can be used in the chemical industry or be further processed into gasoline or kerosene. The details are given in Fig. 1.

3. Technology of BTL production

All the BTL-processes that are currently under development follow the same fundamental principles. In a first step usually a high proportion of water containing biomass has to be grinded and dried. The next step is gasification of the dried biomass to the syngas. By this chemical synthesis carbo-hydrogen chains are formed from carbon monoxide and hydrogen. The Fischer–Tropsch-synthesis is well known since quite a long time and it was used in Germany during World War II to synthesize fuel from coal. The technical problem is that the technology of the coal-to-fuel synthesis used in huge facilities cannot simply scaled down to the smaller facilities needed to produce BTL. Moreover, today environmental concerns have to be taken into account that played no role in a war economy.

The most difficult step is the production of the syngas from the dried feedstock. This part of the conversion process is a thermo-chemical conversion, in which the gasified biomass is decomposed into the main components hydrogen and carbon monoxide. The control of this process is a complicated but very important part of the conversion because the product gas has specific properties in order to be usable for synthesis. In Germany the BTL-process is

actively researched by four laboratories: Choren Industries, CUTEC-Institute, FZK-Institute, and Technical University of Freiberg. The processes researched at these institutes share the same basic conversion steps, but in their details they differ considerably. These differences lead for example to different requirements regarding the kind and state of the feedstock. Hence, in the end an overall evaluation of BTL is not possible but one has to distinguish between the different processes. At present only the Choren process has reached the stage of turning to a demonstration plant on an industrial scale. Therefore, it seems appropriate to use the implementation plans of Choren industries as a guideline when modeling the system aspects of producing BTL fuels. The Carbo-V process offers a number of advantages compared to the production of bio-ethanol and biodiesel. The high temperature combustion in the Carbo-V gasifier yields in connection with the following process steps a high-grade gas that is free from tar, chlorine and sulphur. In the Fischer–Tropsch synthesis, carbon and hydrogen are recombined into long chain paraffin and waxes. The synthetic diesel is then derived from the raw synthesis product in a multistage process [6]. Because the specifications of fuel can fine-tuned by altering the form and length of the fuel molecules. It is possible to match the requirements of the engine constructors – hence, the terms "synfuel" and "designer fuel". This fine-tuning cannot be achieved in the currently used conventional fuel refining processes. The possibility to optimize engine and fuel in a consistent process leads to very low emission combustion, which is an important side effect of BTL. Another advantage is that the available biomass per hectare is larger because the whole plant can be used and not only parts of it as is the case with bio-ethanol or first generation biodiesel. Finally one should note that as any form of biomass may be used – not only biomass containing high proportions of sugar or starch – monoculture is not essential and at least partly, extensive cultivation may be cost-effective [7,8]. In 1998 Choren Industries started the operation of a pilot plant in Freiberg, Germany to test the Carbo-V process with a variety of feedstocks. In 2003, the first industrial prototype plant was put into operation and the first synthetic fuel from wood shreds was produced.

In October 2007, the first industrial scale plant was started to operate in Freiberg. It has to convert about 10 tons anhydrous biomass to 2.5 tons sun diesel with a planned yearly output of 15,000 tons per year and it needs a feedstock of about 60,000 tons anhydrous biomass.

In the meantime this study with the critical evaluation of the rapidly increasing use of biofuels has been cited in several media, journals and reports of international organizations. Some of these publications considered so called "second-generation" biofuels as a promising option in order to overcome the concerns about the presently marketed biofuels [9,10]. For the production of synthetic fuels, first a synthesis gas is produced from the biomass by means of gasification. In a second stage, synthetic fuel is produced out of this gas and therefore, a typical process is the Fischer–Tropsch synthesis. In principle several types of biomass including wood and cellulose or lignin containing plants can be used as a raw material. Also the use of many non-edible plants would be possible, which should avoid negative implications due to competition with the food production.

Different types of synthetic fuels can be produced in this type of processes. The most common ones made from biomass are:

- BTL: biomass-to-liquid. A synthetic fuel with similar fuel properties as conventional diesel.
- SNG: synthetic natural gas. A possible replacement of natural gas.
- DME: dimethylether. A fuel with similar properties as LPG (liquid petroleum gas).
- Ethanol.
- Methanol.

The same type of process can also be used with fossil resources e.g. for the production of GTL (gas-to-liquid) using natural gas or coal-to-liquid (CTL). So far such fuels are not marketed. The first commercial plant worldwide with an annual production capacity of 15,000 tons BTL (biomass-to-liquid) per year should be commissioned in 2008. The conversion plant is erected in Freiberg, Germany by the company Choren. A second larger plant is planned to be erected in Schwedt, Germany with an annual production of 250 Mio. l of fuel. The fuel from the first plant should be used for the first tankful of cars sold by Volkswagen and Daimler Chrysler.

This paper aims to compare the environmental impacts over the full life cycle of using BTL-fuels with fossil diesel or petrol. The following questions are addressed and answered in this paper:

- What are the environmental impacts of using BTL fuels compared to fossil diesel?
- What is the importance of fuel combustion in relation to the total environmental impacts caused by using the fuels?
- How high is the reduction in the global warming impacts compared to fossil fuels?
- What are the results of a comparison with biofuels already available on the market and investigated in a former study?
- What are the yields per hectare compared to other types of biofuels?

The life cycle inventory from well-to-tank of several types of so called biomass-to-liquid (BTL) fuels has been elaborated in a report [11]. Results of the comparison based on the energy content delivered to the tank are discussed in a public LCA report [12] and that LCA has been critically reviewed according to the ISO 14040 standards.

The life cycle inventory of the use of BTL fuels in passenger cars (tank to wheel) and for the transportation services provided by cars can be found. The functional unit is the transportation of one person over 1 km in a passenger car. The life cycle impact assessment is elaborated. The results of this LCA are compared with results from similar LCA studies on BTL fuels. Some methodological issues concerning the differences of so called well-to-wheel studies and full life cycle assessments or cradle-to-grave studies are clarified. The life cycle inventory data on fuel combustion can be found in an annex, which is available for ecoinvent members only. This life cycle assessment of using BTL fuels follows in general the normal procedure of an LCA. The LCA has not been critically reviewed according to the ISO 14040 standards [12].

4. Technology and production processes

From the study of the above discussed plant, we can draw conclusions on the dimensions of the full scale plant, which presumably has started put into operation around 2010 at the location of Lubmin, Germany. The production capacity of this full scale plant will be about 250,000 tons of sun diesel. Taking the proportions of the Freiberg industrial scale plant, the full scale plant needs a feedstock of around 1 million tons of anhydrous biomass. The crop yield per hectare depends on a lot of factors: what kind of energy plant is employed, the quality of the soil, climate, the use of fertilizers, the use of herbicides and pesticides, etc. This alone constitutes a complex system which is worth to be investigated by SD methods, because, for example, the incentives to use herbicides not only depend on the kind of crop but also on climate, soil, and political regulations; the development of the quality of the soil over time depends on the type of plant that is grown, but also on the volume and kind of fertilizers employed; the cultivation method

(monoculture, use of herbicides) influences the biodiversity which feeds back to the amount of infestation. In a SD-model the yield per hectare will be an interesting parameter (or maybe a variable) for which sensitivity analysis may produce interesting insights into the substitution potential of BTL, the need and the prospective amount of subsidies, etc. For the moment, let us assume an average value of biomass produced on cultivated land of 15 tons anhydrous mass per hectare. In this case an area of cultivable land in the order of 700 km^2. Because in Germany even rural areas are quite densely populated, 700 km^2 of cultivable land can very well mean that the feedstock for one full scale plant has to be grown on an area of about 1000 km^2. Given the size of Germany and the intensive use of land for other purposes the number of full scale industrial BTL plants is presumably, better treated as a discrete, not a continuous number [13].

4.1. Pre-treatment

Biomass, however, is different from coal in many respects; the most relevant relates to feeding. Biomass requires significant pre-treatment to allow stable feeding into the gasifier without excessive inert gas consumption [14]. Several pre-treatment options can be chosen and the two most promising are (1) torrefaction and (2) flash-pyrolysis to produce a bio-slurry. In this assessment pre-treatment by torrefaction is assumed. Torrefaction is a mild thermal treatment in which CO_2 and H_2O are evaded and the material is made brittle and very easy to mill. The process is suitable for a wide range of biomass materials and has a high energy efficiency of up to 97%. The torrefied material can be handled and fed to the gasifier within existing coal infrastructure [15]. In addition to the requirement to pre-treat the biomass for feeding, it may also be desired for purpose of densification of the material. Due to the smaller volume transport costs are reduced and the stability of the gasifier operation is increased, due to the higher energy density of the feed. However, in the approach in this paper no pre-treatment prior to transport is performed; pre-treatment is carried out prior to gasification.

4.2. Gasification

The heart of the process is a pressurised oxygen-blown entrained flow gasifier. This technology was identified as optimum technology for biosyngas production as it has the advantages of: (i) high efficiency to biosyngas [16], (ii) fuel flexibility for all types of biomass e.g. wood, straw, and grassy materials, (iii) suitability for scales of several hundreds to a few thousand megawatt, and (iv) possibility to operate on coal as back-up fuel [17]. Entrained flow gasification for coal is a well-established and commercial technology.

4.3. Biosyngas conditioning

The raw syngas from the gasifier needs significant cleaning and conditioning and treating to be suitable for catalytic synthesis. A typical gas condition line-up comprises gas cooling, water–gas shift, CO_2 removal, and impurities removal (e.g. H_2S, COS, HCN, volatile metals). Cooling can be achieved with a cooler or water quench. The advantage of a cooler is that the latent heat in gas can be utilized, however, in the case of biomass firing, there is an increased risk of fouling due to the relative high alkaline and chloride concentrations compared with coal. In a water quench fouling problems are avoided. Except for the gas cooling, the biosyngas conditioning and treating is similar to fossil-based syngas e.g. a coal-to-liquid (CTL) plant. Biosyngas can be cleaned to meet FT specifications with proven and commercial available technologies. There are no biomass-specific impurities that require a totally different gas cleaning approach [18].

4.4. Fischer–Tropsch synthesis

Fischer–Tropsch synthesis is an established technology and the two companies Shell and Sasol have already commercialized their FT technology. It is assumed that a commercial FT process is applied in the BTL plant.

5. Production of BTL fuels

The life cycle inventory of BTL fuel production has been investigated in a European research project (RENEW5) and documented electronically. Different conversion plant developers provided data of the conversion processes. The data are mainly based on technical modeling of such plants, which is based on experiences and knowledge gained from the research work done in the RENEW project. Life cycle inventories of transport services with BTL fuels, where so far no reliable first-hand information is available (e.g. emission profiles of power plants, concentration of pollutants in effluents or the use of catalysts) and assumptions are based on literature data. Thus, sometimes it is difficult to distinguish between different process routes because differences could not be investigated.

We like to emphasize that the different conversion processes investigated in this study have different development degrees. Thus, data presented in the paper represent the current development status of the respective technology. According to the authors a lot of effort was used in order to investigate LCI data as accurate as possible [19]. All conversion concepts are based on their optimal technology. Four concepts are investigated on a scale of 500 MW biomass input and one was investigated based on 50 MW biomass input. Some conversion concepts might be improved by increasing the plant size up to 5 GW, this has not been considered in the LCI study [19]. The RENEW partners UET and Choren work closely together for the planning of the first commercial plant.

The products produced by the different process chains are not 100% identical with regard to their physical and chemical specifications. All interpretations based on the data investigated in this study must consider the herewith-linked technology background [19]. Here we show the conversion rate from biomass to fuel in terms of energy, the plant capacity and the production volume per hour. The BLEF-DME process has the highest conversion rate followed by the cEF-D process. The ICFB-D process has a rather low conversion rate (biomass to fuel) because it produces large amounts of electricity as a by-product. The electricity is only burdened with direct air emissions from the power plant, but not with the production of biomass. This is a worst-case assumption for the BTL fuel and reflects the project idea of mainly producing fuel. A further fuel investigated in the LCI study is dimethylether produced from black liquor in paper plants [19,20]. The use of dimethylether is mainly foreseen for the use with trucks. So far it is mainly discussed in Scandinavian countries. It is excluded here for the discussion on passenger cars in the Swiss context, because reliable information on exhaust emissions was not available.

The biomass to liquid (BTL) technology is one of the most promising technologies in the fuel sector. A technology is required to bridge the gap between today's biodiesel and ethanol fuel and the fuel of the future hydrogen. This technology must use biomass and not be subject to any limitations of use in either today's engine or foreseeable next-generation engines. These demands can be fulfilled using biomass gasification and a subsequent synthesization to fuel. As BTL technology makes it possible to harness the energy from all sorts of biomass, the spectrum of usable biomass will be extended considerably. The yield per hectare could be

increased significantly compared to first-generation biofuels (up to 4000 l of fuel per cultivated hectare according to information from the Fachagentur Nachwachsende Rohstoffe). BTL offers Germany a great opportunity to become more independent from fossil energy sources and could thus be a vital ingredient in the medium to long-term safeguarding of supply in the fuel sector. As it also has the potential to reduce carbon dioxide emissions by over 90% compared to fossil fuels, BTL can also make an important contribution to the mitigation of climate change.

In addition to its technical, climatic and supply advantages, the BTL technology could also safeguard existing employment and indeed generate new jobs in plant construction and agriculture. If biomass energy is generated from domestic resources, this improves the economic value of rural areas and provides the agricultural sector with a new market. Both this innovative synthetic fuel and its production in Germany are also of great significance from an industrial point of view. Germany plays a leading role today in the field of BTL technology, and the extension of this would also serve to open up new export opportunities. Due to its high quality and the fact that its properties can be optimized systematically during synthesis, BTL is an ideal fuel for the next generation of internal combustion engines. It can also be used without problem in jet and turboprop engines. BTL can thus be considered one of the few fuel options available for aviation besides fossil kerosene. In its fuel strategy, the German government has therefore stated that BTL fuels have great potential to safeguard supply, mitigate climate change and provide added value in rural areas, and in addition to providing financial and active support for this implementation report, it already promotes a variety of BTL fuel projects, one of the aims being to provide answers to unresolved questions regarding the technology and to provide an ecological and economical evaluation of these second-generation biofuels. The Federal Ministry of Food, Agriculture and Consumer Protection (BMELV), has been taken lots of initiative using the promotion to pursue a comprehensive strategy in the production of synfuels using biomass. The promotional measures not only include the narrower technical development of BTL processes, but also cover the complete production chain, from cultivation and harvesting to the conditioning of adapted biofuels. The BMELV's promotional measures, thus cover the complete BTL production chain, from research and development projects on provision and cultivation processes in the joint energy crop project EVA, through the conditioning and logistics of biomass being examined in the joint BioLog project, and the project of the Technische Universität Bergakademie Freiberg in Saxony and the Forschungszentrum Karlsruhe aimed at setting up demonstration plants to fuel synthesis in the methanol-to-synfuel (MTS) process. Flanked by academic projects on economical, ecological and other non-technical questions, the promotional measures of the German government, with the participation of reputable businesses, are pushing development forwards throughout the production chain. The German government is also working to provide good conditions for the further development of these fuels through introduction of the Biofuel Act [21] and has helped Choren Industries to fund the construction of a first commercial BTL plant in the Saxon town of Freiberg. Interest in the BTL technology is now also very strong at a European level. The EU Biofuels Directive issued in 2003 requires biofuels to be given a market share of 2% (based on the energy content) by 2005, increasing to 5.75% by 2010. BTL is expected to play an important role in the follow-on regulations, which are currently being drawn up. In the well-regarded, Well-to-Wheels analysis, which was carried out by the Joint Research Centre of the European Commission with the European Council for Automotive R&D (EUCAR) and the European petroleum industry (CONCAWE) [22], the outstanding potential of BTL as a climate-friendly fuel option was clearly shown. The recently established European Biofuels Technology Platform is also dedicating a large part of its activities to second generation biofuels. If BTL fuels are to become competitive, industrial BTL production in Germany must be made possible. Therefore, BTL Implementation report is an important step in the right direction.

The schematic line-up of the integrated biomass gasification and Fischer–Tropsch synthesis (BTL) plant is shown in Fig. 2. The heart of the process is a pressurised oxygen-blown entrained flow gasifier. This technology is the optimum technology for biosyngas production as it has the advantages of: (i) high efficiency to biosyngas, (ii) fuel flexibility, (iii) scalability from hundred to a few thousand megawatt, and (iv) possibility to operate on coal as back-up fuel. Biomass requires significant pre-treatment to allow stable feeding into the gasifier without excessive inert gas consumption. Torrefaction is one of the most promising routes, as it has an efficiency of up to 97% and torrefied biomass can be handled and fed to the gasifier with existing coal infrastructure. The raw syngas from the gasifier needs significant conditioning and treating to be suitable for catalytic synthesis. Biosyngas can be cleaned to meet FT specifications with proven and commercial available technologies. There are no biomass-specific impurities that require a totally different gas cleaning approach. Fischer–Tropsch synthesis is an established technology and the two companies Shell and Sasol have already commercialized their FT technology. It is assumed that commercial FT processes are applied in BTL plants. To determine the (economic) optimum scale for BTL fuel production a simple logistics system based on local biomass (i.e. no overseas import) was used. The fuel production costs are composed of the costs for the biomass feedstock material, transport, transhipment, storage, pre-treatment, and the conversion (gasification, cleaning, synthesis, and product upgrading).

In the assessed system, it is assumed that the BTL plant is located in the centre of a circular forest area. The radius of the area, and resultantly the average transport distances, depends on the scale of the BTL plant, i.e. on the amount of biomass feedstock required. Woody biomass from the forest is chipped and dried to 7% moisture. The dried chips (4 €/GJ_{BM}) are transported by truck to a BTL plant. On site of the BTL plant, the biomass is pre-treated by torrefaction with 97% efficiency, to yield a material that can be fed to the gasifier and allows stable gasification. The pre-treatment costs are fixed at 1.5 €/GJ of pre-treated material. In the oxygen-blown entrained flow gasifier the biomass is converted into biosyngas with 80% chemical efficiency. The raw biosyngas is cooled, conditioned, and cleaned from the impurities. The on-specification biosyngas is used for Fischer–Tropsch synthesis to produce C5+ liquid fuels. Conversion efficiency from biosyngas to FT C5+ liquids is 71%. All FT liquid products are equally considered as a fuel. The capital costs for the BTL plant are calculated with the derived equation. Annual capital (CAPEX) and operational (OPEX) costs are calculated with a depreciation period of 15 years (linear), a required IRR of 12%, operation and maintenance (O&M) costs of 5%, and a plant availability of 8000 ha per year. In Fig. 3 below, the cumulative FT fuel production costs are shown for five typical scales. The production costs decrease from 30 €/GJFT for a 50 MWth plant to just above 15 €/GJFT at a scale of 8500 MWth. The latter scale of the projected Shell Qatar plant is comparable to a conventional oil refinery. At large scale, the biomass costs of 7.3 €/GJFT make up half of the fuel costs. At small scale, the investment costs are determining cost item, i.e. two-third of the fuel costs. The results are given in Fig. 3.

The transport, transhipment, and storage costs are only a small cost item, independent of the scale and related transport distances. The results also show that no advantage can be taken from decreasing the plant size, as the decrease in transport costs is completely outweighed by the increasing investment costs. The economy of BTL plants is very dependent on the production scale and large-scale facilities are required to benefit from the economy of scale. Upon increasing plant sizes, the decrease in investment

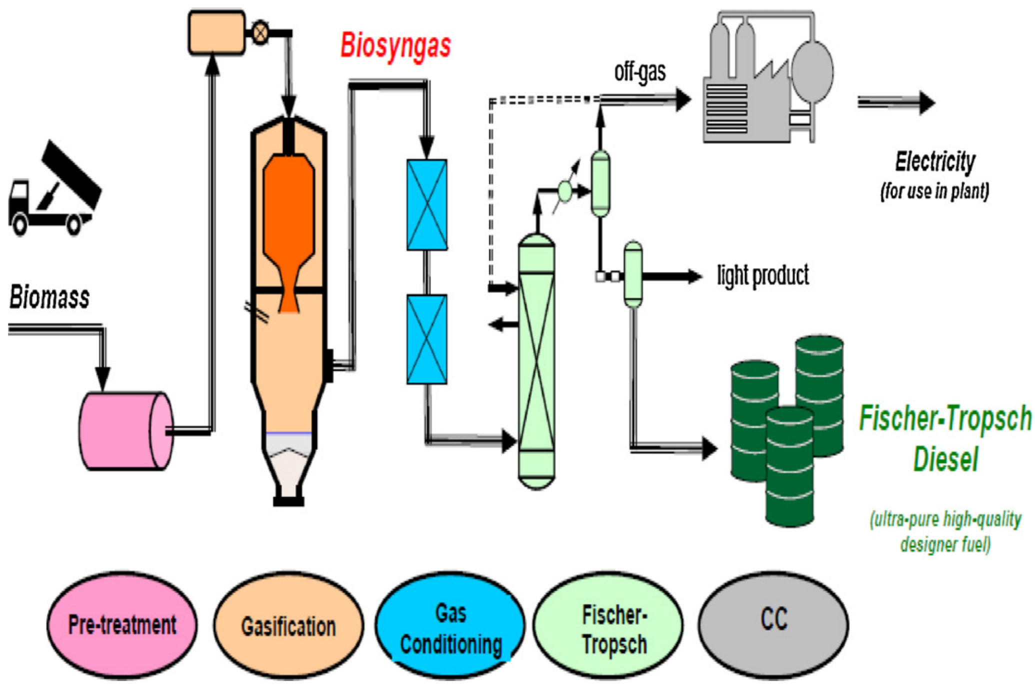


Fig. 2. Schematic line-up of the integrated BTL plant.

costs is much more significant than the increase in transport costs. Large-scale plants in the gigawatt range yield the lowest fuel production costs. In large BTL plants, the FT fuel production costs are approximately 15 €/GJ or 55 €ct/L. This means that at the current oil price of ~60 $/bbl the biomass-based Fischer–Tropsch fuels are competitive. The scope of this study was to answer the question: "what is the (economic) optimum scale for BTL fuel production". Considering all aspects related to required production capacity, implementation aspects, biomass logistics, and fuel production economy, according to the authors "The optimum scale of a BTL plant lies in the range of 2,000 to 4,000 MWth (or 16,000–32,000 bbld)".

5.1. FT oil or green motor fuel from biomass

Franz Fisher and Hans Tropsch first studied conversion of syngas ($CO + H_2$) into large number of useful organic compounds in 1923.

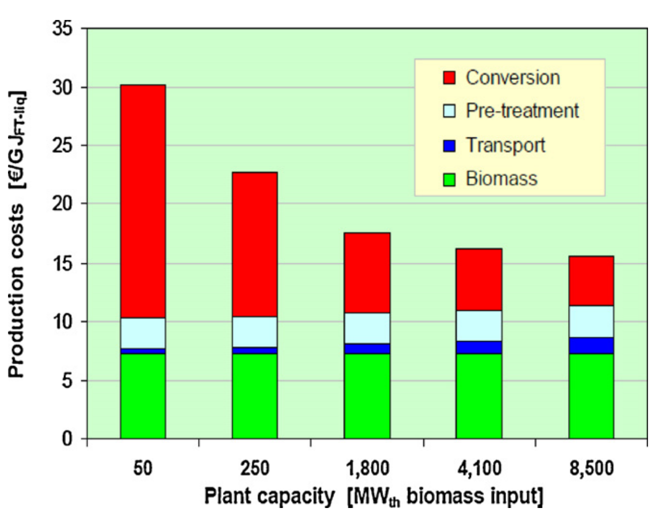


Fig. 3. Scale dependency of FT fuel production costs. For illustration: 15 €/GJ$_{FT}$ ≈ 55 €ct/L.

The syngas produced by gasification of biomass can be converted into large number of organic compounds. The process of converting CO and H_2 mixture into liquid fuels or hydrocarbons over transition metal catalyst is known as Fisher–Tropsch oil (FT oil) or green motor fuel. The FT synthesis processes have flexibility in feedstocks (coal, biomass, natural gas) and the fuel produced by FTS process contains low sulphur. The major drawback of FTS process is the polymerization in the process which yields very high molecular mass waxes which need to be hydrocracked to produce green diesel. Some of the recent publication indicates that the use of FT process technology for biomass conversion to synthetic hydrocarbon may be promising and carbon neutral alternative to conventional fuels.

5.2. Fischer–Tropsch diesel and naphtha

FT diesel and naphtha may be transported with existing diesel and gasoline transportation infrastructure. Blends of zero-sulphur gas-to-liquids (GTL), Fischer–Tropsch naphtha into petroleum diesel fuel could markedly improve winter-time cold flow of diesel fuel, while still maintaining normal diesel fuel properties and avoiding profitable jet-fuel diversion. This discovery could open up previously unheard-of market opportunities for GTL liquids, as most refiners think of GTL diesel rather than GTL naphtha as a potential ultra-clean diesel fuel blendstock. Most petrochemical makers think of GTL naphtha as a superior ethylene cracker feedstock. But new tests show GTL naphtha could enjoy a wider.

5.3. Methanol

MTSynfuels (methanol-to-synfuels). Like Fischer–Tropsch-processes (FT), the process is designed to produce liquid fuels from synthetic gases. Like the FT process, syngas is the starting material for the MtSynfuels® process, which can be produced from various fossil fuels and renewable raw materials. The syngas must meet the same purity requirements and have the same composition (i.e. $H_2/CO = 2$) as is usual for FT synthesis. The subsequent

conversion of syngas to methanol is exothermic, as in the following reactions:

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

The methanol synthesis variant developed by Lurgi works at pressures of 50–100 bar and at temperatures between 220 °C and 280 °C with a Cu–Zn–Al_2O_3 catalyst.

6. BTL diesel production costs

In above discussion, the relation between the specific TCI of a BTL plant and the plant scale (i.e. production capacity) is determined. In this section, the production costs of the BTL diesel fuel are calculated with a simple model. The aim is to determine the (economic) optimum scale for BTL fuel production. The fuel production costs are composed of the costs for the biomass feedstock material, transport, transshipment, storage, pre-treatment, and the conversion (gasification, cleaning, synthesis, and product upgrading). To calculate the production costs of BTL Fischer–Tropsch fuel an approach was used based on a case of a simple logistics system based on local biomass (i.e. no overseas import).

7. Comparison of BTL fuels with fossil fuels

We investigate the transport service provided by passenger cars and compare this with the fossil reference. This includes the necessary infrastructure for roads and its maintenance and the production, maintenance and disposal of cars. Thus, this is the evaluation of the full life cycle of transport services, which is also commonly referred to as “cradle to grave”. Fig. 4 shows a comparison of transports with passenger cars operated with BTL-fuel and fossil fuel. The comparison is presented for the use of non-renewable energy resources. The ranking of the different types of fuels is the same as already discussed on the basis of one MJ of fuel delivered to the tank [23] of interest is the difference between the transport with cars operated on BTL-fuel and the reference cars operated with petrol. The inventory of a EURO3 passenger car is taken as the baseline. The use of non-renewable energy resources can be reduced by 37–61% due to the use of the investigated BTL-fuels.

Compares the emission of greenhouse gases in the life cycle of BTL-fuels and fossil fuels. The emission of greenhouse gases is reduced between 28% and 60% compared to the petrol car if BTL-fuels are used. Thus, most BTL-fuels investigated here would meet the present criteria of 40% GWP reduction as foreseen in Fig. 4.1 shows the Eco-indicator 99 (H, A) scores of the different alternatives [24]. Most BTL-fuels have higher impacts than the fossil reference if the full method is used. The most important impact is the land use. For energy crops like short-rotation wood not only the land occupation has a negative effect.

The transformation of set-aside land to highly intensive agricultural area makes an important contribution of about 20% to the total impacts. BTL-fuels based on straw show environmental impacts not much higher than the reference. In this case the land occupation is considerably lower because the major part is allocated to the produced wheat grains. If land use would be excluded from the assessment (as proposed in a sensitivity analysis by Zah et al.) most BTL fuels would achieve results comparable to the fossil reference. The BTL-fuel made in the most efficient process from forest wood has lower impacts than the fossil reference. This can be explained by the lower negative impacts of forests on biodiversity compared to agricultural land. This fuel would achieve the criterion for tax reduction, which is not to have higher environmental impacts than fossil petrol [24]. The use of forest residues, which is not investigated here, would be even more favourable.

The impacts caused by for carcinogenic emissions are negative (see Fig. 4.2) for the BTL from short-rotation wood because the uptake of certain heavy metals from soil during biomass growing is assessed higher than the emissions in the life cycle shows the results with the method ecological scarcity 2006 [25]. Also here some heavy metals are removed from the agricultural soil during plant growing and thus results in the category emissions into top soil are negative. All BTL-fuels made from agricultural biomass have higher environmental impacts than the fossil reference. The emissions of nitrate are comparably higher for miscanthus. This is the reason for the relatively higher contribution from emissions into groundwater. For some fuels environmental impacts due to waste management are quite important. This is due to the disposal of ashes and slag from the conversion process. It might be possible to further improve the disposal or even to reuse the remaining as fertilizers in biomass production. So far such options have not been considered in the modeling of the conversion plants.

8. Comparison with other biofuels

A comparison with other biofuels is possible based on the data investigated by Jungbluth et al. [26,27] and evaluated by Zah et al. [28]. Fig. 4.3 shows a comparison with the fuels evaluated in those studies. All BTL-fuels from agricultural biomass have higher environmental impacts than the fossil reference. Some BTL-fuels from agricultural biomass have only slightly higher environmental impacts than the reference. BTL-fuel from forest wood is a good possibility concerning reduction of greenhouse gas emissions and protection of the environment. This shows that it is possible to produce BTL-fuels, which are competitive to fossil fuels from an environmental point of view. But, it also shows that the use of agricultural biomass needs further improvements in order to achieve this goal with BTL. In comparison to other already available biofuels like e.g. rape methyl ether the results are in the same order of magnitude. These results confirm the findings were reported in Zah et al. [28]. Many biofuels derived from agricultural biomass are not preferable from an environmental point of view if the full life cycle is taken into account. But, BTL-processes may also use wood from forestry or biomass residues. In comparison to short-rotation wood or other energy crops, this would substantially reduce the environmental impacts.

It is not possible to draw general conclusions for the comparison of synthetic BTL-fuels with e.g. plant oils, ethanol or methyl ethers. For all types of renewable fuels the used biomass is an important factor for the environmental impacts. Thus, there are better and worse fuels in each category. A general advantage of BTL-fuels compared to other biofuels, as claimed in some literature, is not confirmed by our study. Fig. 4.4 compares the Eco-indicator 99 (H, A) results of a BTL-fuel made from wood with fossil diesel. One sees that results for most stages are the same for both fuels. Only fuel combustion and fuel production are different. Diesel causes higher impacts during combustion especially due to the CO_2-emissions and higher emissions of regulated pollutants, but distinctly lower impacts during fuel production [29].

BTL is CO_2 – neutral as its combustion only releases the CO_2 contained in the biomass. Therefore, on a net basis it does not add to the level of greenhouse gases in the atmosphere. BTL fuel is also free of aromatic components which can be serious air or water pollutants [30]. BTL is basically free of sulphur. Sulphur in fuel, when it burns is converted to sulphur oxides which are pollutants, contributing to poor air quality and adding to the problem of acid rain.

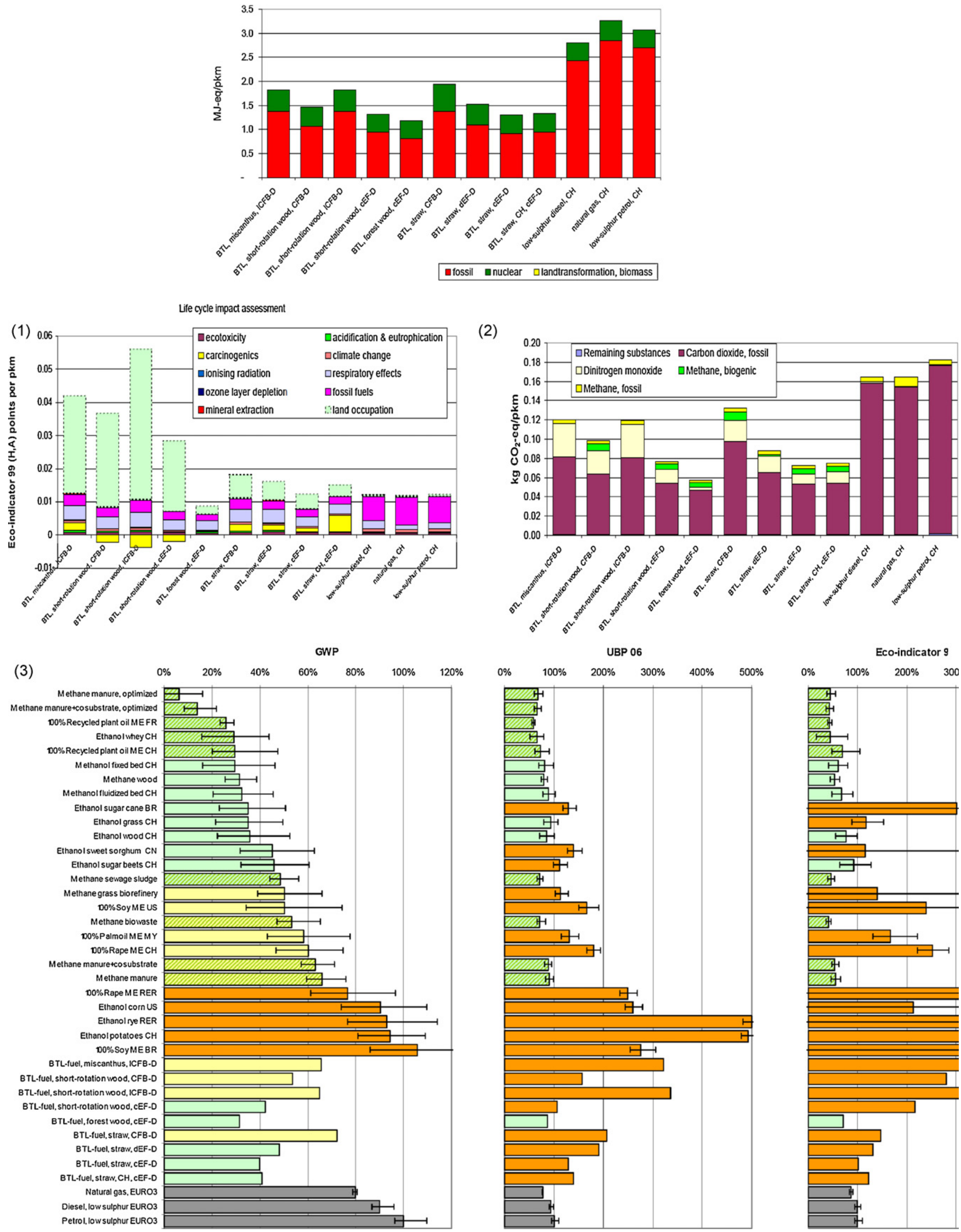


Fig. 4. Non-renewable cumulative energy demand of the transport service (MJ-eq/pkm). (1) Global warming potential of transport services (kg CO_2-eq/pkm) over a time horizon of 100 years. (2). Eco-indicator 99 (H, A) score of the transport service (points/pkm) [25]. (3) Relative comparison of passenger transports using different category indicators (basis pkm of transport). Reference for all fuels is the use of a EURO3 petrol car. Life cycle impact assessment with global warming potential, Eco-indicator 99 (H, A) and ecological scarcity 2006 (Pt-points) [26–28]. (4) Detailed comparison of Eco-indicator 99 (H, A) results of BTL from short-rotation wood and diesel in different stages of the life cycle.

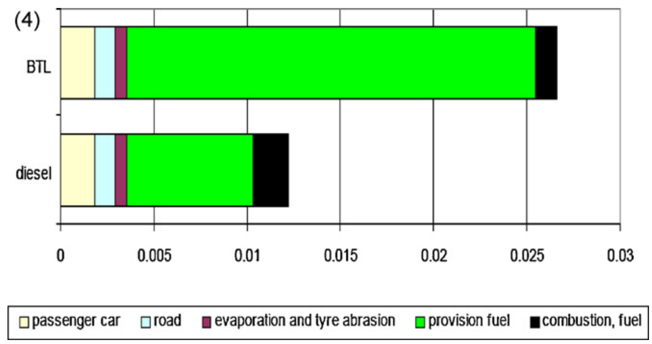


Fig. 4. (*Continued*).

However, sulphur has one good quality in fuel in that it provides lubricity, thus reducing wear on engine parts. Biodiesel is high in lubricity but low in sulphur. It therefore, can be used as an additive to synthetic fuel or reduced-sulphur petro-diesel to limit engine wear as sulphur emissions are reduced. Prospects are better for blends than for pure biofuels. When confronted with the idea that biomass to liquid technology might present a threat to biodiesel, representatives of the European biodiesel industry proposed that there was enough room in the market for both. In Germany, Volkswagen and Daimler Chrysler started projects on BTL-technology. Volkswagen called their fuel "Sun Fuel" while Daimler Chrysler's fuel was named "Biotrol" (biomass + petrol = biotrol). Now-a-days both companies work together with a company called Choren and call the fuel "sun diesel". Choren is located in Freiberg (Saxony) and has developed the so-called and patented "Carbo-V®" gasification process [31–33].

9. Comparison with other studies

The scope of this study was to answer the question: "what is the (economic) optimum scale for BTL fuel production". Considering all aspects related to required production capacity, implementation aspects, biomass logistics, and fuel production economy, according to the authors "The optimum scale of a BTL plant lies in the range of 2,000 to 4,000 MWth (or 16,000 to 32,000 bbld)" [34–38].

9.1. BTL fuels

Despite that the GTL technology has been known for decades, recently it started to be considered for large-scale manufacturing of fuels and chemicals (mainly from coal and natural gas) only. The application of syngas from biomass in GTL production [biomass-to-liquid (BTL)] is more recent [39–43]. The typical fuels, which can be obtained from GTL processing and which are suitable for use in road transport are given in Fig. 5 [44–48], while their main properties, together with the properties of their oil-derived analogues [49–64] and the results are presented in Table 1 [65–70].

9.2. Products from F–T synthesis

As Fig. 6 indicates, GTL processing is similar to oil refining, since a number of products is obtained. Thus, GTL synthesis can be regarded as an alternative refinery run on feedstocks other than oil–natural gas, coal or biomass. The total energy efficiency of typical breakdown of fractions in oil refining and in GTL processing is lower than that of oil refining (80% versus 85–90%), but the 20% GTL thermal losses can be partly recovered via heat integration in the process units [71,72].

Typical breakdown of fractions in oil refining and in GTL processing. GTL processing has an important technological difference with oil refining. The optimum oil refining output by fractions is spread amongst a number of products, is relatively constant and can vary within relatively narrow margins. Conversely, the optimum breakdown of fractions in GTL synthesis is more flexible [73,74] and can be optimized to a larger extent versus certain products, most often versus middle distillates are given in Fig. 6. Another feature of GTL processing is that the heavier fractions consist of high quality lubricants and waxes (<C20), but not of heavy fuel oils like in oil refining. GTL lubricants and waxes can easily find a good market, including in the food industry, while the market for heavy fuel oils is generally less profitable, along with the environmental burdens they cause [73,74].

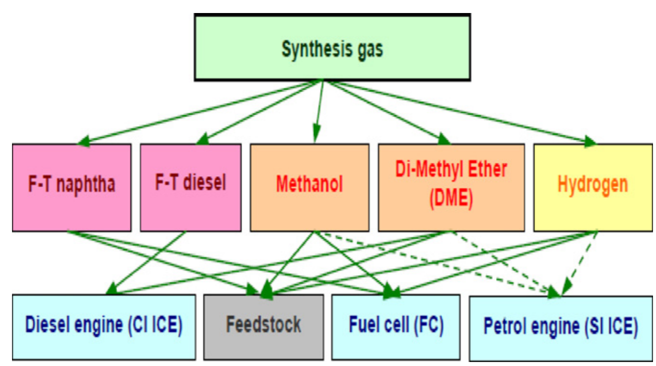


Fig. 5. Fuels obtained via GTL processing of syngas.

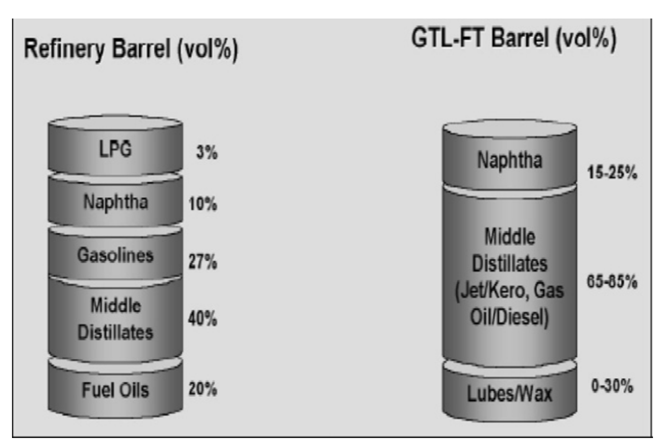


Fig. 6. Total energy efficiency of refinery barrel (vol%) and GTL-FT barrel (vol%) [71–78].

Table 1
Main properties of oil-derived and BTL fuels.

	Chemical formulae	Energy content (MJ/L)	Density (kg/L)	Octane number	Cetane number	Chemical feedstock
Oil petrol	C4–C12	31.2–32.2	0.72–0.77	90–95	–	No
Oil diesel	C15–C20	35.3–36.0	0.82–0.84	–	45–53	No
Oil naphtha	C5–C9	31.5	0.72	50	–	Yes
BTL naphtha	C5–C9	31.5	0.72	40	–	Yes
BTL diesel	C12–C20	33.1–34.3	0.77–0.78	–	70–80	No
Methanol	CH_3OH	15.4–15.6	0.79	110–112	5	Yes
Di-methyl-ether	CH_3OCH_3	18.2–19.3	0.66–0.67	–	55–60	Yes
Hydrogen	H_2	8.9	0.074	106	–	Yes

Source: Adapted from [49–70].

An additional and important environmental advantage of GTL products is that, unlike oil derivates, they are quickly biodegradable. The degradation rate of GTL diesel reaches 60% within only 28 days in anaerobic conditions. GTL products consist almost entirely of linear paraffins (C_nH_{2n+2}), with less than 5% aromatics on mass basis, compared to 10–30% aromatics for oil derivates [75].

Since paraffins have higher hydrogen-to-carbon ratio than aromatics, this implies lower density and higher (4–5%) energy content on a weight basis for GTL fuels compared to oil-based fuels. Due to the lower density, the volumetric energy content of GTL products is however lower than that of oil derivates. In addition, linear paraffins are more easily and efficiently transformed into other products than aromatics and branch paraffins [75]. Finally, all GTL products are virtually sulphur free (sulphur content below 1 ppm), since a large part of sulphur compounds is removed during the syngas production step. The remaining small traces of sulphur are further separated before the GTL synthesis, because the catalysts for GTL processing are extremely sensitive even to very low contaminations of sulphur [73,75].

9.3. BTL (GTL, F–T) naphtha

Naphtha is a light fraction from oil refining and GTL processing (see Fig. 6) with similar to petrol properties. Nevertheless, naphtha is not appropriate for use in petrol engines (SI ICE) because of its low octane number. Due to the lack of any large direct application as a motor fuel, at present naphtha is used mainly as a feedstock for further conversion (at the expense of additional energy losses, emissions and costs) to petrol, ethylene, etc.

In the future naphtha could also become an attractive energy option for FC [76]. When hydrocarbons are used as hydrogen carriers for FC, their relative hydrogen content (hydrogen-to-carbon ratio) is the governing "fuel" parameter, while the octane number and the energy content are not important. The higher the hydrogen-to-carbon ratio, the better the hydrogen carrier. The relative hydrogen content of naphtha is higher than those of oil-derived naphtha (due to the larger content of linear paraffins) and petrol (due to the slightly shorter carbon chain) as shown in Fig. 6. The lack of sulphur in BTL naphtha is an important advantage over oil-based fuels for FC applications, since the proton exchange membrane (PEM) FC are very sensitive even to negligible sulphur contaminations. Such direct market realization of BTL naphtha (without further processing to other products) would improve the efficiency of BTL processing in terms of energy use, emissions and costs [76].

9.4. BTL (GTL, F–T) diesel

Historically, F–T diesel was the first motor fuel obtained via GTL technologies. The feasible upper limit of the "natural" F–T diesel fraction in GTL processing is 75%. A larger F–T diesel yield can be achieved via transforming other GTL products, but always at the expense of additional energy losses, emissions and costs.

GTL diesel has similar to oil-derived diesel physical and chemical properties. It is therefore fully compatible with current storage, handling and distribution infrastructure for oil-based diesel, thus its logistics would not involve additional capital costs [39]. For the same reasons the use of F–T diesel generally does not require modifications in diesel engines (CI ICE). F–T diesel has poorer lubricity compared to conventional oil-derived diesel. This is due to the lack of polar molecules (including hydrocarbon-based and sulphur-based compounds), which are removed during the hydroprocessing step of GTL. Hence, if a CI ICE is run on pure BTL diesel, the addition of some lubricant components is necessary [40]. Alternatively, if it is blended with conventional diesel up to 20–30%, no fuel additives or engine modifications are necessary. Because of the lower volumetric energy content on equal terms running a diesel engine on GTL diesel will result in a small fuel economy penalty of 3–8% [41]. This fuel economy penalty can be compensated to a certain extent by injection timing changes [42].

Nevertheless, GTL diesel demonstrates several clear performance advantages over conventional diesel. The cetane number is higher, because linear paraffins in the diesel boiling range have much higher cetane numbers than branch paraffins [35]. Besides the better engine performance (smoother operation, improved start-up, less noise), the higher cetane number of F–T diesel allows its blending with lower quality conventional diesel, which otherwise cannot be utilized as an automotive fuel [39,43,44]. In such a way secondary benefits are incurred at the refineries, since by such blending the extent of utilization of the diesel refining fraction is enhanced. On the other hand, linear paraffins, which prevail in GTL diesel, have poorer cold flow properties than branch paraffins, which are more widely presented in oil-based diesel [35]. The lack of sulphur in F–T diesel also cuts the SO_2 emissions from combustion. Apart from the reduced sulphur content, the lower density of F–T diesel also implies lower particulate matters (PM) emissions.

9.5. Biomethanol

Methanol (CH_3OH) known also as "wood alcohol" is a commodity chemical, one of the top ten chemicals produced globally [45]. It is liquid at ambient conditions, which facilitates transportation and handling. The main application of methanol is as feedstock for producing formaldehyde (H_2CO) – 65% of world methanol production whose demand is driven by the construction industry [45].

With regard to the automotive application, because of its high octane and low cetane number, methanol is better suited for SI ICE than for CI ICE. Besides the higher octane number, methanol has another advantage over petrol – the content of oxygen that improves combustion and thus, reduces local-polluting emissions. However, methanol contains only half of the energy of petrol, i.e. on equal terms a methanol tank would have to be twice as large as a petrol tank to give the same driving range. Owing to its

advantages, at the end of 1980s/beginning of 1990s methanol was widely used in the USA as an automotive fuel (mixed with petrol in low or high – up to 85%, concentrations) or converted into a petrol additive (methyl-tertiary-butyl-ether, MTBE). However, at present the automotive application of methanol in ICE is completely abandoned.

While the use of MTBE is negligible and continuously declining. The reason is that methanol poses a number of serious health and safety concerns. The ingestion of only 25–100 ml methanol can cause blindness and even death. Methanol can be in-taken not only orally, but also via accidental spillage on the skin. The health hazard for unintended ingestion of methanol is further increased by its complete solubility in water. The risk for accidental spillage and contamination of ground water is strengthened by the powerful corrosiveness of methanol. For this reason the use of methanol requires application of only high-cost stainless steel storage components [46,47]. Methanol also burns with almost invisible flame, which makes difficult to detect fires in their initial stages [48]. As a consequence, methanol has shown 25 times higher fatalities than petrol.

Low blends (up to 5%) of methanol with petrol would reduce to a large extent (but not avoid completely!) these safety and health concerns. Nonetheless, low methanol blends appear to be difficult and costly for market implementation due to the need to overcome consumers' resistance and the bad experience from the past. Although methanol is not regarded as a feasible automotive fuel for ICE anymore, it is presently employed as ingredient in the production of biodiesel from oilseeds. On average, 1.1 weight units of methanol are mixed with 10 weight units of vegetable oil to obtain 10 units of biodiesel. It is considered (especially in Europe) that methanol could be a suitable hydrogen carrier for on-board reforming for FC in the future. Since FC vehicles are supposed to require a higher quality of servicing than the vehicles equipped with ICE, the FC application of methanol could reduce the health and safety risks. Conversely, methanol demonstrates some important advantages over other hydrocarbons – potential hydrogen carriers. It has one of the highest hydrogen-to-carbon ratios (4:1) amongst all hydrocarbons. Another key advantage of methanol is its low reforming temperature. Obtaining hydrogen from methanol requires 200–300 °C, compared to 500 °C for ethanol, 850 °C for natural gas and 850–1000 °C for petrol.

The low processing temperature simplifies the layout of the reformer and reduces its cost. The infrastructure for conventional automotive fuels can be also relatively easily retrofitted (at a reasonable cost) to handle methanol. In addition, the application of methanol as a hydrogen carrier for FC could be facilitated by the mature status of methanol production from fossil feedstock. Methanol manufacturing from synthesis gas is a well-established technology that already earned large economies of scale. In 2002 there were about 38 million tons of methanol production capacities worldwide, operated at 80% utilization rate. The near-term expansion of methanol capacities is projected to bring the world production potential up to 39–41 million tons per year [52,53]. This large-scale production is a key factor for methanol to be one of the few alternative fuels, which are cost competitive to conventional fuels. Despite that currently biomass is not used in industrial methanol manufacturing, the availability of such refined production technologies and distribution infrastructure, along with the growing security of energy supply concerns, could facilitate the penetration of biomass as a feedstock for methanol synthesis. Besides the on-board reforming to hydrogen, methanol could also be employed directly in FC, in the so-called direct methanol fuel cells (DMFC). In DMFC, methanol is injected straight to the cell's anode and reacts to form electricity and CO_2. Nevertheless, the direct application of methanol in FC is regarded mainly as a long-term option. DMFC are at a very early stage of development and have a much lower efficiency than PEM FC that use hydrogen – 15% versus 40% respectively [54–59].

9.6. Bio-di-methyl-ether (BIO-DME)

DME (CH_3OCH_3) is a synthetic fuel, which does not occur naturally in petroleum. It represents a novel fuel (first tests started in the middle of the 1990s) that is still at an experimental stage [60]. Originally DME has been manufactured via methanol de-hydration, but more recently the direct DME production from syngas has been examined.

The direct production route appears to be more energy and cost efficient, since it involves one process instead of two processes – methanol synthesis and methanol de-hydration. At present, the annual world output of DME is only 100,000–150,000 tons [61–63]. Currently the largest application of DME is in aerosol spray cans, but not as a fuel [64], therefore the availability of data about fuel DME is scarce. Similar to LPG, DME is gaseous at ambient conditions, but liquefies at moderate pressure (5–8 bar) [64,65], hence DME could be mixed with LPG. It is suggested that low-concentration DME blends with LPG (up to 10–20%) require none or only minor system modifications.

DME can also exploit the already existing LPG infrastructure (where available), which could become a prime factor for its market penetration. By analogy with LPG, DME might potentially be used for non-transport purposes as well e.g. as a household fuel, moreover that DME handling is somewhat safer than that of LPG [64]. For safety reasons, the addition of an odour component to DME is however necessary, since naturally DME is odourless like LPG [65].

DME has a higher cetane number than oil-based diesel, which makes it more suitable for application in CI ICE rather than in SI ICE. Owing to its oxygen content that improves combustion and to the lack of carbon-to-carbon bonds, DME burns cleaner and quieter in CI ICE than oil-derived diesel [64,65]. Conversely, DME contains only about half of the energy of oil-based diesel, which increases fuel consumption and requires more than a twice larger fuel storage tank aboard the vehicle. The additional storage volume is due to the mandatory 80–85% filling rate, as a safety margin in case of high ambient temperatures, similar to LPG. The use of DME in CI ICE also requires some engine modifications – replacement of all plastics and rubbers with metal-to-metal seals from nonsparking metals more sophisticated injection system, etc. In particular, the dedicated injection system appears to be a key technical challenge for the automotive use of DME [64,66]. Since the DME injection system completely differs from that for diesel, simultaneously running a CI ICE on DME and diesel (dual-fuel performance) is not possible [67]. DME has also poor lubricity and viscosity, hence lubricating additives is needed at 500–2000 ppm level.

All these technical and technological drawbacks, combined with the prevailing high production cost, make DME more a medium to long-term alternative, rather than a fuel of tomorrow [66–68]. Owing to its high hydrogen-to-carbon ratio (3:1), DME could be in theory considered also as a hydrogen carrier for on-board reforming for FC. Nevertheless, due to the complications with the on-board storage of gaseous fuels and considering the availability of other, more suitable liquid hydrogen carriers (e.g. methanol and GTL naphtha), the option of using DME as a hydrogen carrier for FC does not appear promising.

9.7. Biohydrogen

Hydrogen (H_2) is not available independently in the atmosphere, but is always combined with other elements. Hence, before being used it has to be extracted from various compounds e.g. via the syngas route. Currently, hydrogen is produced mainly from natural gas and to a lesser extent from oil derivates (totally 77% of all

hydrogen production), while its production from biomass is at an experimental stage [69]. This is due partly to the more sophisticated manufacturing of syngas from biomass compared to natural gas, but also to the much lower relative hydrogen content of biomass vice versa natural gas [70].

There are two ways of employing two different fuels in the same engine – bio-fuel, when the engine runs on either fuel or dual-fuel, when the engine runs simultaneously on both fuels (fuel mixture). About 60% of world hydrogen production is used in ammonia production, followed by 23% in oil refining and 9% in methanol synthesis. In such a way, only 8% of global hydrogen production is left as merchant hydrogen that potentially can be used as an automotive fuel [77].

In principle, it is more correct to consider hydrogen as an energy carrier but not as a fuel. Unlike all other automotive fuels, hydrogen is carbon-free that makes it the fuel with the cleanest combustion in ICE as well as the most appropriate fuel option for FC. Another advantage of hydrogen is the higher octane number compared to petrol, which favours its use in SI ICE. Nevertheless, hydrogen is regarded as a more viable energy option for FC, due to the much higher efficiency of FC compared to ICE. Despite these advantages, at present the application of hydrogen as an automotive fuel faces some techno-economic constraints – low volumetric energy density, complicated storage and handling, higher cost per kW of FC compared to ICE, etc. Due to these constraints, the application of hydrogen in SI ICE (either pure or blended with petrol) and/or in FC is currently at an experimental stage [51,52,71]. However, a significant amount of work to improve the performance of hydrogen technologies is undergoing. The issues with hydrogen and FC are examined thoroughly in a number of other studies of the JRC Institute of Energy and in particular within the operation of the European Hydrogen and Fuel Cells Technology Platform [78].

10. Use of BTL-fuels in passenger cars

A basic inventory of passenger cars with EURO3, 4 and 5 standard using diesel or petrol has been elaborated. The inventory of the most important air emissions during the combustion of BTL-fuels is based on available information from measurements made within the RENEW project by Daimler Chrysler, Renault and VW ([79–81], see Table 2). The following air emissions also regulated by the EURO standards have been reported: NO_x, CO, hydrocarbons, particulate matter and CO_2. Only some direct comparisons between using diesel and BTL in the same power train and under the same conditions are published. Most information on emissions with BTL-fuels is only published on a relative scale compared to EURO4 standards. These figures cannot be directly interpreted as an emission reduction compared to the use of diesel because also power trains using diesel will have emissions lower than the maximum limit. In general the figures show a high variation depending on the power train and the test conditions. So far no information investigated independently from possible fuel producers and car manufacturers is available. Real emissions of driving cars are not necessarily equal to the emissions measured under standardized conditions. Due to this reason, average emission figures used by are partly higher than the EURO limits.

In order to achieve comparable results to the previous study, it is necessary to determine the emissions of an average EURO3 car using BTL. In a first step reduction factors are estimated based on the available information. These factors shown in the last row (see Table 2) are used to calculate the emission with the data available for EURO3 diesel cars [79–81]. The rough estimation is mainly based on the information available for the reduction factors between diesel and BTL use. The large variation and the relative scale in the publications make it difficult to estimate these emissions. But, the later evaluation shows that the direct emissions are only of minor importance for the evaluation of the total environmental impacts.

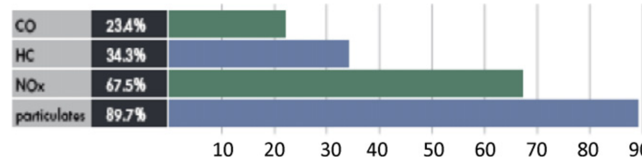


Fig. 7. Comparison of exhaust emission levels of refinery diesel and BTL fuel (Golf TDI 103 kW, New European Driving Cycle (NEDC)); engine control unit tuned for maximum reduction of NO_x.
Source: Volkswagen AG.

The measurements on BTL-fuel have been made with the type of fuel produced by the centralized entrained flow gasification (partner UET in the RENEW project) [74]. No differences are accounted for the other types of BTL-fuels investigated in this project, because measurements were not available.

According to [75] the energetic fuel consumption can be assumed to be equal for BTL and diesel, but differences in lower heating value per kilogram have to be considered. Other parts of the life cycle inventory as e.g. other air emissions and the used infrastructure for roads are considered the same as investigated for EURO3 cars. Data of the operation of passenger cars is shown in Table 2. The inventory describes the fuel use and emissions due to the operation of the car over one kilometre. On the right side of the table, the basic data can be found. The last column shows the literature data used for the estimation of standard diesel emission factors [72].

The sulphur content of BTL-fuel is estimated roughly with 1 ppm [73] and the one of diesel with 50 ppm [75]. Sulphur dioxide emissions are calculated from these contents. The life cycle inventory of the transport service includes the fuel consumption and combustion, operation of the car, the production of roads and cars and their disposal. In addition, the maintenance of all necessary items is included. The inventory is calculated with an average occupation of 1.59 persons per car [76,77].

A recent German study investigated some of the BTL-pathways also investigated here [78]. The approach used in that LCA is quite different from the modeling taken here because allocation problems are tackled with the approach of system expansion. This means a credit with an alternative product is given for those by-products not used in the system [78]. Also the basic concepts used for the modeling such as background data or impact assessment are not necessarily the same. The study concludes that BTL-fuels from short-rotation wood are an environmental benefit with regard to the category indicators climate change and use of abiotic resources, but that there are disadvantages with regard to several other category indicators. For the comparison of different types of conversion concepts, it also concludes that the conversion efficiency is quite important. The authors do not see any clear preference for one of the conversion concepts, as there are still different lines of development within the conversion concepts. The approach how by-products, mainly electricity and heat are tackled also quite important for the conclusions from this study [78]. The results of the study for the BTL-fuel production concerning the emissions of greenhouse gases are quite different compared to a recent study published by EUCAR, CONCAWE and JRC [79]. We compare here the WTT emissions calculated by [80] with the figures calculated in the RENEW LCA and they are considerable lower. The RENEW LCI study, which forms the basis for the evaluation give CO_2-eq emissions between 20 and 60 g/MJ of fuel delivered to the tank while the WTW-study calculated about 5 g CO_2-eq/MJ. Below one sees the results of comparable synthetic fuels made from wood. The results are shown in Fig. 7.

Table 2
Air emission reductions of different passenger cars using BTL-fuel and low-sulphur diesel and estimation of reduction factors compared to EURO3 diesel cars for this study. Negative figures stand for higher emissions than the Refs. [79–81].

	NO_x	PM	CO	HC	HC + NO_x	Source	Manufacturer	Test specification
EURO4 (g/km)	0.25	0.025	0.5	0.05	0.3			
EURO4 to BTL	0%	22%	75%	80%		Degen [80]	Daimler Chrysler	No adaption
EURO4 to BTL	30%	−20%	50%	80%		Degen [80]	Daimler Chrysler	NO_x optimization + particle filter
EURO4 to BTL	30%	−30%	90%	85%		Degen [80]	Daimler Chrysler	NO_x optimization
EURO4 to BTL	20%	30%				Heinl [81]	VW	Adjusted injection rate
EURO4 to BTL			90%	80%		Heinl [81]	VW	Independent of data set
EURO3 to BTL	2%	28%	59%	55%		Degen [80]	Daimler Chrysler	No adaption
CEC Diesel to BTL	0%	45%	70%	60%		Heinl [81]	VW	To CEC diesel fuel
Diesel to BTL	0%	26%	50%	75%		Rouveirolles [79]	Renault	GTL with conv. diesel, EURO 4
Diesel to BTL	15%	−20%	20%	10%	15%	Degen [80]	Daimler Chrysler	NO_x optimization + particle filter
Diesel to BTL	18%	25%	40%	18%	18%	Degen [80]	Daimler Chrysler	NO_x optimization
Mean EURO to BTL	16%	6%	73%	76%				
Mean diesel to BTL	8%	19%	45%	41%				
Mean all to BTL	13%	12%	60%	60%				
Estimation diesel to BTL	10%	10%	45%	40%		This study		

The differences were discussed with the responsible authors. The following main differences were identified:

- Higher nitrogen input in for the short-rotation wood production (2.5 g vs. 5–6 g/kg DS). This result in about 50% higher N_2O emissions during biomass growing of the data used here compared to only low direct emissions of CH_4 and N_2O are assumed for conversion plant in the Concawe study, because of data gaps. This reduces the greenhouse gas emissions by about 10–20%.
- Infrastructure was not considered in the Concawe study. Infrastructure in agriculture and fuel conversion contributes about 10–20% to the total greenhouse gas emissions in our study.
- Credits for electricity production with biomass power plant are granted in the Concawe study while our study makes an allocation. This is mainly relevant for the ICFB-D and thus for the highest cumulative greenhouse gas emissions.

11. Comparative study of greenhouse gas emissions (GHG) and emissions from GTL, BTL and CTL

The environmental attributes of the conventional and synthetic fuel technologies are assessed by measuring the impact caused through production, transportation and fuel usage, the so-called well to wheel basis or life cycle assessment. Industry studies show that greenhouse gas emissions (GHG) of the "GTL system" are comparable to a refinery system (±5%). The well to tank CO_2 emissions from a GTL production plant are slightly higher than those from a conventional refinery, but are offset by the tank to wheels CO_2 emissions which are up to 4–5% lower. As diesel engines are some 20–30% more efficient, their CO_2 emissions are significantly lower (some 20%) than their equivalent petrol counterparts. Relative to a refinery system, BTL offers clear life-cycle greenhouse gas benefits in the range of 60–90% improvement. The BTL process is able to use waste biomass such as woodchips, which has already taken up CO_2 from the atmosphere during its growth. Burning the BTL fuel in an engine, simply returns the captured CO_2 to the atmosphere.

CTL process has a carbon penalty compared to refinery system due to the high carbon-to-hydrogen (C:H) ratio of coal, the starting feedstock. However, this could be reduced through CO_2 sequestration and other means. The results are shown in Fig. 8. Further improvements in synthetic fuels GHG emissions can be expected from optimized engines (5–10%) and process improvements from focused R&D. Hence GTL could reach a 5–10% GHG emission benefit if compared to refinery diesel and CTL plus sequestration could reach a neutral CO_2 balance in comparison to today's petroleum based fuels [81,82].

12. Prospects

According to Choren, it takes 5 tons of biomass to produce 1 ton of sun diesel and 1 ha generates 4 tons of sun diesel. A plant producing 13,000 tons per year would need the biomass of 50,000 ha. In recent years the German set-aside area amounted to roughly 1 million ha. This could generate 4 million tons of sun diesels, which is about 13% of current diesel use in Germany [83,84]. Daimler Crysler expects that BTL fuels could achieve a market share of 10% in Europe by 2015. Volkswagen cites a study that sees the production potential for BTL at 70 million MT of fuel in the EU-15, which would amount to one third of the fuel currently used by all vehicles (cars and trucks) in the EU-15. The use of carbon dioxide neutral and renewable biomass for the production of fuels is a vital alternative to fossil-based energy resources. However, there are a number of major obstacles to an economically feasible production of biofuels by the BTL process. These are:

- High investment costs.
- Low volumetric energy density of biomass.
- Lack of infrastructure.
- Limitations to the productivity of photosynthesis.
- Availability of cultivable land areas for the production of bioenergy plants, which are in competition with food production.

The low energy density of wood-based biomass in particular, which is the cheapest and most abundant biomass, makes it difficult to convert this source into biofuels. The pyrolysis of lignocellulosic biomass into high-quality bio-oil by using suited catalysts is still the main challenge to the concept of a modern lignocellulosic biorefinery. Once high quality bio-oil is achieved, the subsequent use as direct feedstock or as co-feedstock in conventional refinery

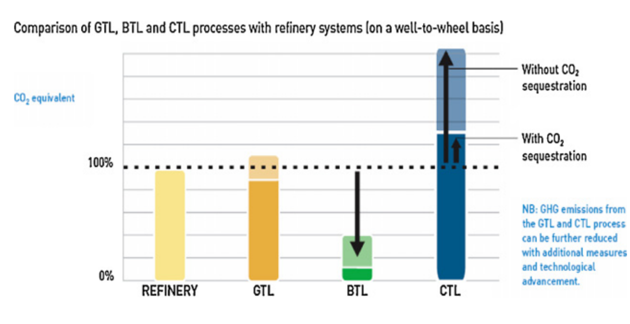


Fig. 8. GHG emissions from GTL, BTL and CTL on a life cycle basis.

processes such as FCC or HT can be envisaged to produce diesel and/or gasoline. Hydro-treating requires high-pressure hydrogen; however, it might be feasible that this hydrogen demand can be satisfied from biomass conversion as well (catalytic steam reforming of the carbohydrate fraction). There are a number of alternatives available for the utilization of biomass-derived feedstocks in a crude-oil refinery, and the development of technology for the production of biofuels will allow a move towards a sustainable economy [85–89]. In a time, in which the focus is on global warming, carbon dioxide emission, a secure energy supply and lower consumption of fossil-based fuels, the use of renewable energy resources is essential [90]. Biomass is one of these renewable resources! Challenges related to the catalytic conversion of wood based biomass remain and have to be addressed in the future research:

1. Understanding the mechanism of the catalytic conversion of lignocellulosic biomass into bio-oil, including structure–property relationships and product distribution.
2. Catalyst development, regarding porosity, acidity, basicity, metal–support interactions, controlled formation of appropriate catalyst particles, improved hydrothermal stability, and resistance to catalyst deactivation [91].
3. Process conditions and large-scale production. The biorefinery approach using wood-based biomass does not compete with traditional crude-oil refining, rather it is complementary to petroleum refining [92].

Alternative fuels: less fuel consumption and emissions, the development of fuels is inseparable from the development of drive systems. With new sources of energy, we utilize additional potential for reducing fuel consumption and emissions. Regenerative hydrogen is the fuel of the future. Used in fuel cell vehicles, it guarantees mobility free of pollutants and CO_2. CNG (compressed natural gas) is a promising option because it contains less carbon than gasoline or diesel [93].

BTL fuels (biomass-to-liquid) of the second generation are largely CO_2 neutral, but are not in competition with the production of food or fodder and can be well adapted to the requirements of internal combustion engines. GTL fuels (gas-to-liquid) are the cleanest and highest-quality sources of energy for diesel engines along with BTL fuels [93].

13. Conclusions

The European Union has adopted a strategy to increase the use of renewable energy resources considerably. The discussion in this paper has shown that amongst the alternative proposals to increase the use of energy from renewable resources for traffic purpose, the biomass-to-liquid technology is most promising. But BTL-production is embedded into a complex dynamic system with several feedback. This complexity makes it hard to evaluate the role of BTL-fuel can play in a strategy of ecological, economical and social sustainability. The use of biofuels is mainly promoted for the reason of reducing greenhouse gas emissions and the use of scarce non-renewable resources e.g. crude oil. The emissions of greenhouse gases due to transport services can be reduced by about 60% with the best BTL-processes using short-rotation wood or straw as a biomass input. This is comparable to other types of biofuels made from agricultural biomass resources and with forest wood, reductions up to 69% are possible. On the other side, there are severe disadvantages from an environmental point of view if fuels are produced from agricultural biomass. The introduction of BTL-fuels made from energy crops would further increase environmental problems mainly caused due to today's agricultural practice. Emissions of substances contributing to eutrophication and acidification are much higher than these of transport services based on fossil fuels. Only one BTL-fuel shows about the same acidification potentials as the fossil fuel car, while all others have higher emissions. Further process improvements are necessary in order to overcome the disadvantage at least regarding acidification. But, the pressure on land and water resource is increased considerable due to the increased production of all BTL-fuels. This would be especially relevant if set-aside land is transformed to intensively use agricultural area. Until now many BTL-fuels produced from energy crops would have higher overall environmental impacts than fossil fuels.

The use of BTL-fuels is more preferable from an environmental point if wood residues can be used or if wood stems from forestry instead of short-rotation plantations. These findings are in line with several former life cycle assessment studies on biofuels. The BTL concepts investigated in this study are modeled for self-sufficient energy supply of the conversion plant and the aim to achieve high fuel yields per hectare. There might be several other ways of development, which are not considered in detail. One possible line of development is the co-production of BTL-fuels together with electricity, heat and feedstock for the petrochemical industry. With such a concept the achievable fuel yields would be lower, but the overall energetic efficiency could be higher. It would also be possible to use other energy carriers than biomass in the conversion plant. One such concept is the use of hydrogen produced e.g. from renewable electricity. This would allow higher fuel yields but therefore considerable supplies of clean electricity would be necessary.

The environmental impacts of BTL-fuels must be re-evaluated if BTL-fuels are introduced to the market. To quantify the real environmental impacts it is necessary to know the type of biomass used and key figures of the conversion plant, in particular the conversion efficiency, amount and revenues of by-products, emissions and wastes. Due to the variety of conversion concepts and possible biomass resources it is not possible to make generally valid statements concerning the overall environmental impacts of BTL-fuels compared to other types of renewable or fossil fuels. Some aspects are not covered in the modeling of this LCA. An important aspect is the impact of land transformation on the carbon stock in soils. The authors are claiming that such land use changes might be well relevant in the assessment of greenhouse gas emissions. Another aspect is the release of N_2O emissions due to the use of fertilizers in agriculture. New research work claims that these emissions might be higher than modeled until today. Synthetic fuel made from biomass (BTL) offers a 90% improvement in CO_2 emissions compared to a refinery and enables the possibility of renewable fuel for transport.

The main statements and findings of this study can be summarized as follows:

- To meet the ambitious biofuel targets of the European Commission a total installed BTL production capacity of 785 PJ is required by 2020.
- TCI costs of BTL plants are typically 60% higher than for corresponding GTL plants.
- Torrefaction is the optimum biomass pre-treatment technology for entrained flow gasification.
- Commercial available technologies can be applied for biosyngas cleaning and conditioning as well as for Fischer–Tropsch synthesis.
- The economy of BTL fuel production is very dependent on the production scale and large-scale facilities are required to benefit from the economy of scale.
- Large-scale plants in the gigawatt range yield the lowest fuel production costs i.e. approximately 15 €/GJ or 55 €ct/L.

14. Glossary

Second generation fuels	Synthetic biofuels are sometimes termed as "second generation" or "advanced" fuels (in contrast to the above mentioned "first generation"). This term is also used for fuels made from biomass resources, which are not edible and are thus not competitive to food production. A third definition of "second generation" fuels refers to the use of lignin, cellulose or hemi-cellulose parts of the plants as a raw material.
Synthetic fuels	For the production of synthetic fuels first a synthesis gas are produced from biomass or another resource by means of gasification. In a second stage a synthetic fuel is produced out of this gas. A typical process therefore is the Fischer–Tropsch synthesis. In principle several types of biomass including wood and cellulose or lignin containing plants can be used as a raw material. Also the use of many non-edible plants would be possible. The same type of process can also be used with fossil resources e.g. for the production of GTL (gas-to-liquid) using natural gas or coal-to-liquid (CTL). Different types of synthetic fuels can be produced in this type of processes. The most common ones made from biomass are: • BTL: biomass-to-liquid. A synthetic fuel with similar fuel properties as conventional diesel. • SNG: synthetic natural gas. A possible replacement of natural gas. • DME: dimethylether. A fuel with similar properties as LPG (liquid petroleum gas). • Ethanol. • Methanol.
SunFuel, SunDiesel	Brand names for BTL-fuels produced by the company Choren and supported by Volkswagen and DaimlerChrysler.

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